3 NSWP ASSESSMENT BY PLAN ACTIVITIES

In this chapter, the committee assesses the performance and current status of the NSWP in terms of a set of nine activities called for in the NSWP Strategic Plan and the two editions of the Implementation Plan as the means to achieve program goals. In its assessment, the committee focused on the activity descriptions in the second edition of the Implementation Plan (OFCM 2000) as providing the most recent and most detailed specification of what these activities should achieve. Three of the nine activities have been assessed together because they overlap extensively. The three foundation documents also called for the NSWP to pursue activities to foster enhanced private sector and international coordination. These crosscutting activities are addressed in the final section of the chapter. Table 3-1 lists the resulting set of assessment categories, which correspond to the major headings of the chapter.

Table 3-1. NSWP Assessment Categories

Section	NSWP Activities Assessed
3.1	Assess and document the impacts of space weather
3.2	Identify customer needs
3.3	Determine agency roles
3.4	Coordinate interagency efforts and resources; set priorities; ensure exchange of information and plans
3.5	Encourage and focus research
3.6	Facilitate transition of research results into operations
3.7	Foster education of customers and the public.
3.8	Crosscutting Issues

3.1 Assess and Document the Impacts of Space Weather

The Assessment Committee determined that this NSWP activity should cover, and has covered, two related but distinguishable types of impacts: (1) the impacts of space weather that make it a safety, security, and economic concern for the Nation, and (2) the benefits that can be gained from space weather forecasts.

3.1.1 Impacts of Space Weather

The NSWP has supported significant efforts to investigate economic and industrial space weather impacts. Such impacts are now discussed in scholarly science journals and in industrial and popular literature. The NSWP has significantly increased overall awareness of space weather and assisted in the compilation of a variety of assessment documents. The following are examples of space weather impacts, many of which are cited in the *NOAA Magazine Online*, Story 131 (NOAA 2006):

- The effects of a March 1989 space weather storm cost two large utilities, Hydro Quebec in Canada and PSE&G in New Jersey, an estimated $30 million in direct costs. Hydro-Quebec's solution to the blackout was to install devices that block storm-induced currents from traveling through its transmission lines. Unfortunately, this solution is extremely complex and expensive ($1.2 billion). Comprehensive real-time protective space weather prediction services could have significantly reduced damages and costs (Quinn 2000).
- In research supported by the National Science Foundation, Forbes and St. Cyr (2004) used a multivariate economic analysis of one cross-state transmission system to conclude that space weather produces congestion in that system, which transmits power from the generating site to the distribution site. For the interval studied—June 1, 2000, through December 31, 2001—they concluded that solar-initiated geomagnetic activity increased the wholesale price of electricity by approximately 3.7 percent, or approximately $500 million. The economic conclusions of this analysis have occasioned some controversy, and further discussions and analyses are in progress.
- An aviation insurance underwriter has estimated that $500 million in satellite insurance claims from 1994 to 1999 were the direct or indirect result of space weather (NOAA 2006, cited under "Satellites" subheading).
- The DOD has estimated that disruptions to government satellites from space weather cost about $100 million a year (Rodgers et. al. 2000).
- Solar-initiated geomagnetic storms in 1994 and 1997 appear to have been the cause of the demise of three communications satellites: U.S. Telstar 401 and Canada's Anik-E1 and Anik-E2 satellites. Total replacement costs were estimated to be $600 million (Baker et al. 1994; Chapline 2000). There is not yet agreement in the community on why the Telstar satellite was lost; the loss occurred on the day following a geomagnetic storm. The pager satellite Galaxy IV may also have been rendered inoperable from space weather effects (Baker et al. 1998)
- Interruptions to high frequency radio communications during the Gulf War in 1991 have been attributed to solar storms (NOAA 2003).
- Space weather information is commonly employed as important operational input for determining launch and on-orbit operations of Space Shuttle and International Space Station (ISS) activities.
- Space weather information is crucial for determining time constraints on astronaut operations external to the Shuttle and ISS (space walks) and for re-entering the vehicle.
- During times of high solar activity, polar airline routes are often diverted to lower latitudes to prevent loss of radio communications and avoid human exposure in case of increased radiation from solar energetic particles. Such flight diversions can cost airlines as much as $100,000 per flight for additional fuel, extra flight crews, and additional landings to refuel. This cost does not include economic and unquantifiable losses to passengers, such as missed connections. Space weather considerations will be included in the current Aviation 2025 architecture study by the Federal Aviation Administration (FAA).

- Civil and military search and rescue missions can be, and have been, severely impeded by anomalous radio communication signal propagation under disturbed ionospheric conditions.
- Many elements of commerce and society have become very dependent on global positioning, navigation, and timing (PNT) systems. A one percent gain in continuity and availability of GPS alone is estimated to be worth $180 million per year (Rodgers et. al. 2000).
- In 2004, NOAA/SEC issued the first-ever space weather event assessment (NOAA 2004). This multi-chapter document highlights the physical events and system effects of the large solar and geomagnetic storms of October and November 2003. NASA contributed essential information to this study and followed on with a publication in *Space Weather* (Barbieri and Mahmot 2004), detailing hardware and communications issues addressed by the agency in the storm's aftermath.

The above examples do not include the intangible societal benefits that arise from better knowledge of space weather and from mitigation actions, based upon this knowledge, that have been implemented in various technologies. Just as buildings can be designed with more assurance that they can withstand earthquakes when the Earth's crust and mantle are better understood, so too can space- and ground-based technical systems be designed more reliably when space weather information becomes more accurate and widely available. If systems are better designed to withstand space weather effects, societal costs such as electrical or communications outages can be avoided or at least made less severe. It is difficult, if not impossible, to place monetary figures on technology disruptions that do not occur because some systems were designed to account for space weather effects where they are deployed. Some estimates can be made from knowledge of the systems and the steps necessary to protect them from destructive interruptions. Much more analysis effort in this area is needed in the future.

Despite an increasing awareness of space weather, assessment and documentation of its effects remain difficult because of industrial or governmental proprietary issues, security classification constraints, and misunderstanding or lack of understanding about space weather hazards. Commercial users of space weather products are hesitant to have their concerns with, and vulnerabilities to, space weather effects publicly highlighted for fear of loss of market share or investor confidence.

Even members of the DOD, where operations routinely involve space systems, are uncertain about how best to assess space weather impacts and capabilities. Recently AFWA undertook a review of the overall contribution of weather to the Air Force Concept of Operations. Although the resulting report, *Value of Weather Services to the Combatant Commands*, concentrated on terrestrial weather, it mentioned space weather, concluding that "…There is some uncertainty that what is currently measured is actually important to the expected impact on military systems….Real measures of success for space-weather elements are not currently available in sufficient quantities to be useful in the Air Force Capabilities Review and Risk Assessment process" (AFWA 2005). As a result of this uncertainty, the study recommended additional research and experimentation in the entire area of space weather determine:

(a) What space weather elements should be measured and forecast?

(b) What kinds of sensors (ground- or space-based) produce the most accurate observations?

(c) What are the capabilities (accuracy specifications) of these sensors?

(d) What space elements should AFWA forecast (what are the customer requirements)?

(e) What are the forecast verification statistics for these forecast elements?

Since this report, additional work has been done to identify DOD's space weather needs, as discussed in the following section. Briefings to the Assessment Committee from the AFWA staff, AFSPC, AFRL, and the Office of Naval Research indicate that these concerns are widely recognized, but the resources and authority to address them are lacking.

The *Space Weather Architecture Study* by the National Security Space Architect (NSSA) contains discussions of the importance of space weather for national security (NSSA 1999). Appendix E of this report contains the key summary recommendations from the NSSA study.

3.1.2 Benefits of Space Weather Forecasting

Tracing the complex chain of causality from the forecast of a space weather event to the economic or social benefits gained may require an interdisciplinary team of economists, scientists, engineers, and practitioners within the affected agency or industry. Further, many space weather impacts and the subsequent benefits of space weather forecasts are unquantifiable. Others cannot be detailed publicly because of their national security sensitivity or because they would reveal information that companies (e.g., satellite operators) might wish to keep proprietary for various reasons. As a result, few in-depth studies of the benefits to society, both economic and social, of space weather forecasts have been done. Past studies have tended to focus on a single technology or application. Nevertheless, the national space weather effort would gain from benefit studies, as such studies would help clarify the value of the NSWP to the public, to Congress, and to the executive branch. Such studies would also provide important guidance for future investments in space weather research and operations.

Finding 3.1. The NSWP lacks a coordinated effort to identify and quantify, where possible, the benefits to society of providing space weather forecasts.

Recommendation 3.1.1. The NSWP should institute a coordinated effort to fund a series of space weather benefit studies that would cover the primary topics of concern to operators of space weather–vulnerable systems.

These studies could include, among other systems affected by space weather, geostationary satellites, aircraft, electric power grids, and PNT satellite systems. Among other results, such studies could provide important information for the design and development of new space weather forecast capabilities by helping NSWP participants understand where to expect the highest returns from investments in such capabilities.

Space Weather and Human Space Exploration

Since time immemorial, human beings have explored the Earth—its lands and seas—and have often endured great personal risk and hardship in doing so. Human exploration into space is also a difficult and dangerous endeavor. Such an endeavor requires great ingenuity and optimism, as well as the courage to take measured risks while attempting to optimize safety and success.

In addition to accepting the risks inherent in riding atop millions of pounds of explosives, the human body must successfully adapt to a unique environment, whether in transit to and from the Moon, Mars, or other destinations in deep space. One unavoidable environmental challenge is the radiation environment—solar and galactic cosmic rays—that fills space above Earth's atmosphere. The environment must be studied and understood well enough that solar storm prediction strategies are effective and available mitigation techniques can be employed. All must be accomplished with sufficient accuracy to allow difficult programmatic decisions weighing risks versus rewards to be made by those held accountable for costs to the taxpayer and for the fate of astronauts.

Some considerable experience exists related to astronaut safety during solar events, although most of it currently derives from experience in low Earth orbit (LEO). For example, the Johnson Space Center made the following report for the solar storm events of October-November 2003 (NOAA 2004):

> "Solar flare activity caused flight controllers to issue contingency directives for the ISS Expedition 8 crew to briefly relocate to the aft portion of the station's Zvezda Service Module and the Temporary Sleep Station (TeSS) in the U.S. Lab. The Expedition 8 crew of Commander Mike Foale and Flight Engineer Alexander Kaleri spent brief periods of time in the aft section of the Zvezda Service Module, which is the most shielded location aboard the ISS from higher levels of radiation. During Tuesday (October 28), there were five 20-minute periods during which the crew was asked to remain in the aft end of Zvezda."

Figure 3-1. The ISS.
Courtesy NASA/SRAG.

Astronauts inevitably note that they are willing to take such environmental risks to be part of humanity's exploration away from our planet. They do so with the understanding that not only mission success but their very survival depends on the scientific and operational communities leveraging the best support each has to offer.

3.2 Identify Customer Needs

Agencies participating in the NSWP have devoted considerable attention and resources to the identification of customer needs in the period since the 2000 NSWP Implementation Plan. NOAA/SEC, for example, has a broad government and commercial customer base that continues to grow as the technologies that can be affected by space weather continue to grow both in number and in the demands placed upon many of the customers' operations. During interviews with the Assessment Committee, SEC staff members reported substantial efforts in identifying and supporting customer needs in the industries and agencies shown in figure 3-2. The SEC staff is also actively engaged in working with nongovernmental (commercial) organizations interested in providing value-added products, services, and data for space weather.

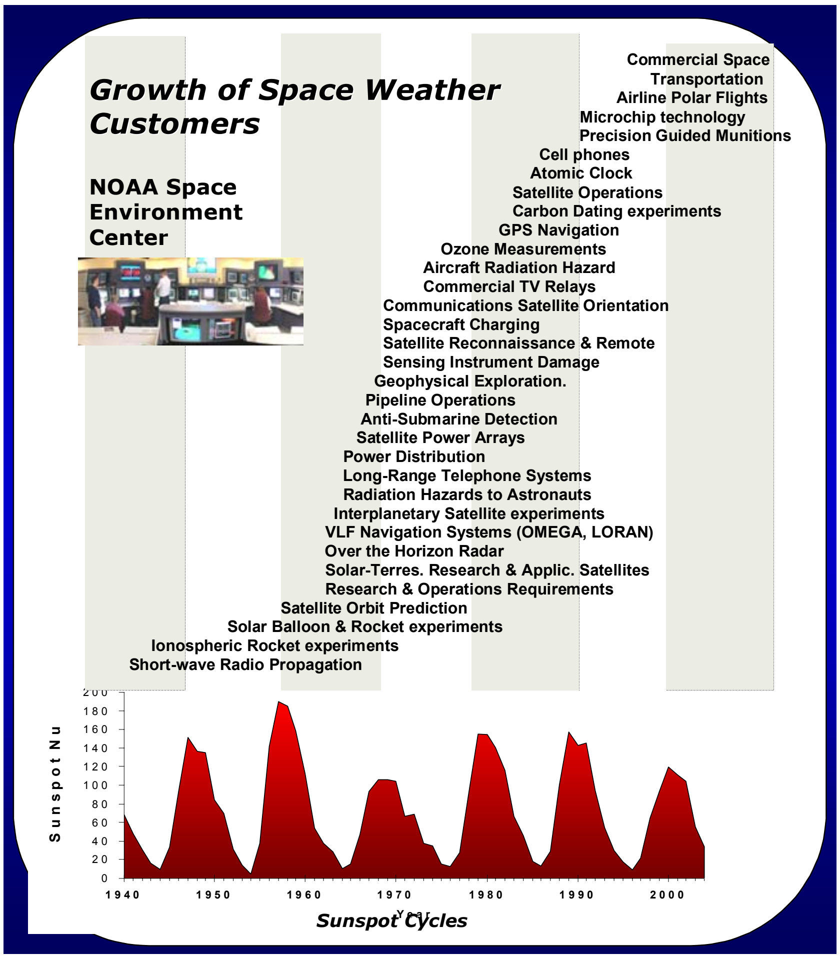

Figure 3-2. Customers of the NOAA Space Environment Center.

Table 3-2 provides a broad overview of space weather hazards as they relate to mission areas within the DOD. One of the primary challenges to DOD space weather service providers (internal DOD, other government, or commercial) is the interface with a changing customer base. Mission area program managers and system or hardware operators may rotate every 2 or 3 years. Thus, in some mission areas, space weather providers may have as much or more knowledge about customer needs as the customers themselves.

When the NSWP began in 1995, space weather needs of civil aviation were rarely mentioned, although such needs were widely recognized for DOD missions, especially high-altitude reconnaissance missions or those in polar regions. Significant changes in civilian requirements have occurred since the end of the cold war, especially in the past five years as an increasing number of flights use routes that cross the northern polar cap between North America and Europe or the Far East. Table 3-3 lists space weather impacts on civilian aviation and the capabilities needed to mitigate them, as identified in the FAA Air Traffic Organization advisory user needs analysis that is currently under consideration.

Table 3-2. DOD Mission Areas Supported by Space Weather Requirements

Space Weather Requirements	DOD Supported Mission Areas
Scintillation	*Communication *Positioning, navigation, and timing Intelligence, surveillance, reconnaissance, ballistic missile defense
Radio frequency interference	*Communication, Intelligence, surveillance, reconnaissance, ballistic missile defense
Radiation and charging	*Spacecraft *High altitude aircraft
Electron density	*Communication *Positioning, navigation, and timing Intelligence, surveillance, reconnaissance. ballistic missile defense
Neutral particle density	*Spacecraft Intelligence, surveillance, reconnaissance, ballistic missile defense
Ground induced currents	*Electric power
Aurora clutter	Intelligence, surveillance, reconnaissance, ballistic missile defense

*Area of commercial/civilian interest in addition to DOD mission relevance.

Table 3-3. Space Weather Impacts on Aviation and the Observation and Forecasting Capabilities Needed to Address Them

Impact on Aviation	Needed Capability
HF communication outage in polar regions	Real-time observation of polar HF radio blackouts. Forecast of polar radio blackouts 12 hours in advance. Graphical depiction of forecasting radio blackouts.
HF communication outage in mid and low latitudes	Real-time observation of mid- and low-latitude HF radio blackouts due to geomagnetic storms, graphical product defining intensity, frequencies affected, and geographical boundaries. Forecast of geomagnetic activity up to 6 hrs in advance.
Navigation disruption or outage	Real-time observation of mid- and low-latitude GPS disruption, graphical product defining intensity and geographical boundaries. Forecast of geomagnetic activity up to 6 hr in advance. Graphical depiction of forecast GPS disruption.
Biological radiation exposure	Provide CAMI access to WMSCR distribution network, with alerts targeted to airlines and FAA Command Center. Incorporate estimated dosage from energetic particle events into cosmic radiation exposure estimates. Longer lead-time and more accurate prediction.

The Space Situational Awareness Information Office, which supports AFSPC in Colorado Springs, has undertaken a study of long-term space-customer needs and likely shortfalls. As communicated to the Assessment Committee, this study emphasizes that even under the most optimistic of scenarios, space-based observing capability will not meet customer needs in the space weather arena.

A similar conclusion was reached by the NSSA in the *Space Weather Architecture Study*. Again based on identified needs, this study concluded that observational capabilities will not meet minimum requirements associated with national security needs (NSSA 1999).

Fostering Collaborations among Academia, Industry, and Government

The Boulder Valley in Colorado has one of the larger concentrations in the world of institutions related to solar physics. Recognizing the potential for collaboration, scientists and administrators at these institutions voluntarily organized the Boulder Solar Alliance in 2005. This organization fosters communications and interactions among solar researchers, identifies joint projects and opportunities of mutual interest, and promotes activities that can contribute to national and international research activities. One such activity is the National Space Weather Program.

Figure 3-3. Participants in the Boulder Solar Alliance.

The technical capabilities and the breadth of intellectual expertise within the Boulder Solar Alliance span the Sun-Earth system. They encompass basic research; numerical modeling; data mining and assimilation; delivery of services; technology transfer; advanced education; practical training; and instrument design, development and fabrication. Member institutions include basic research organizations, such as the Federally-funded High Altitude Observatory of the National Center for Atmospheric Research (NCAR), and academic laboratories, such as the Laboratory for Atmospheric and Space Physics and the Joint Institute for Laboratory Astrophysics of the University of Colorado. The university is currently investigating ways to refine and coordinate its undergraduate and graduate programs in solar and space physics, including avenues for involving scientists from the Boulder Valley in its educational mission. Private not-for-profit groups with complementary research interests include the South West Research Institute's Office of Space Studies and Colorado Research Associates, a division of Northwest Research Associates.

NOAA's Space Environment Center in Boulder builds upon such research to pursue applied and operational research activities, culminating in space weather monitoring, forecasting, and the development of national mitigation strategies. The Boulder Solar Alliance anticipates its members will eventually include local space industry partners such as Ball Aerospace and Technology Company, Raytheon, and Lockheed-Martin.

3.3 Determine Agency Roles

The NSWP is a confederation of agencies (table 3-4) that coordinate their space weather activities as individual agency funding and statutory directives permit. Although each agency has demonstrated considerable interest in, and commitment to, the NSWP, each member organization must adhere to its own mission statement and authorizing legislation.

Nevertheless, progress has been made in interagency efforts and resource coordination, information exchange, and planning. Probably because of the agencies' significant interest in the program, as evidenced by the close interactions of the cochairs of the Committee for Space Weather with each other and with the other three agency representatives on that committee, there has been an extraordinary—and at times novel—leveraging of interagency and intra-agency resources. The attendant planning and information exchanges fuel and sustain these successes.

Table 3-4. NSWP Agency Roles

Department of Commerce/ NOAA	NOAA has the mission of describing and predicting the Earth's environment. The SEC hosts an operational forecast center and research activities. The National Geophysical Data Center is responsible for national sensors (principally those operated by NOAA) and World Data Center archives.
DOD	The DOD develops operational models of the solar terrestrial system and develops and flight-tests new sensors. The Air Force forecast center provides basic and specialized support for military communications, surveillance, and warning systems that operate in or through the upper atmosphere or near-Earth space. The Air Force Research Laboratory and Naval Research Laboratory develop models for DOD operational use and develop or support development of sensors to measure the space environment.
NSF	NSF is responsible for maintaining the health of basic research in all areas of solar and solar-terrestrial science.
NASA	NASA's mission is space exploration and study of the Sun-Earth system. For space weather, the focus areas are causes of solar variability and impacts of variability on Earth and on human exploration of the solar system.
DOI	Within the DOI, the USGS participates in an international network of 98 geomagnetic observatories, several of which contribute data in real time to the Air Force and NOAA/SEC forecast centers.
DOE	Within the DOE are elements that study space weather in the context of nuclear weapons detection and elements concerned with space weather impacts on electrical energy transmission.
DOT	Within the DOT, the FAA is responsible for regulating and promoting the U.S. commercial space transportation industry. The FAA is the licensing and regulatory authority for the nascent space tourism industry. The DOT also fields a GPS-based capability to support en route, terminal, and precision approach operations for airports and heliports.

Among the notable achievements in individual agency and multi-agency activities are the following:

- The annual Space Weather Week meeting of approximately 300 users, government and service providers, and researchers increases in size each year and has been emulated by the European Space Agency (ESA).
- The American Geophysical Union established, with partial support from NSF, the on-line technical journal/magazine *Space Weather, The International Journal of Research and Applications,* with a hard copy *Space Weather Quarterly,* containing selected articles from the on-line edition. This journal facilitates communication across agencies and with the non-Federal communities.
- The NSF's annual competition for space weather grants is partially supported by the DOD and NASA.
- The Community Coordinated Modeling Center (CCMC) at NASA Goddard Space Flight Center operates with NASA, DOD, and NSF support.
- In several cases, DOD, NASA, NSF, and NOAA have coordinated their research and archival efforts in space weather.
- A new NSF Science and Technology Center, the Center for Integrated Space Weather Modeling (CISM) has been funded for a 5-year term, with the possibility of an additional 5-year extension. NOAA participates in CISM.
- New model and forecast products (related to the ionosphere, energetic particles, and the Sun) from NOAA/SEC and AFWA are in the pipeline or in test beds.
- The USGS provides real-time data from five observatories, which allows the Air Force to compute a real-time index of planetary geomagnetic activity called the Kp index.
- The DOD has funded several MURIs to support targeted academic research for DOD and dual DOD-civilian needs.
- The annual meeting of the American Meteorological Society includes sessions focused on space weather.
- The AFSPC has funded improvements to solar irradiance forecasting and neutral thermosphere density modeling for use in satellite drag specification.

Space Weather and Spacecraft Anomalies

Solar storms often produce anomalies in instruments and spacecraft flying in the Earth's space environment, even though these space flight elements are designed using the best current information on the environment. The solar storm events of October–November 2003 produced numerous anomalies on NASA and other spacecraft, many of which were itemized and discussed by Barbieri and Mahmot (2004) in an article in *Space Weather*.

Large numbers of qualitative and quantitative anecdotes exist from the earliest days of space flight related to space-encountered anomalies. A recent one, pointing out the importance of solar event alerts, is from a solar event that interfered with the use of Geostationary Operational Environmental Satellite (GOES) spacecraft for international search and rescue. NOAA GOES satellites form part of the Cospas-Sarsat, a multinational search and rescue effort that uses satellites to detect and locate emergency beacons carried by aircraft, ships, or individuals in distress. The NOAA U.S. Mission Control Center (USMCC) in Suitland, Maryland, encountered a series of GOES anomalies (radio interferences in this case) in early November 2004. One of the interference episodes was identified on the NOAA Office of Satellite Operations Daily News Report on November 3, 2004:

> The GOES-9, GOES-10 and GOES-12 satellites experienced radio noise during November 3 and 4, 2004. The GOES-9 and GOES-12 events occurred on November 3 and the GOES-10 event was during November 4. These satellites have several systems that receive 401 to 406 MHz, including the Satellite Aided Search and Rescue repeater. Of the events, the GOES-12 event was the most severe in both magnitude and duration (about 100 minutes). NOAA/NESDIS would like to receive the solar radio burst alerts. The frequencies of interest are 245 MHz, 410 MHz, and something around 2.0 GHz for our [the NESDIS] telemetry link

The problem was attributed to solar radio burst emissions, particularly in the low 400 MHz range. This event occurred during a 7,200 solar flux unit (sfu) burst on 410 MHz from a solar flare in Active Region 696.

The USMCC staff emphasized the importance of understanding problems that occur with search and rescue (SAR) operations, and the staff requested space weather alert support for this event. The requirement was passed on to AFWA at Offutt Air Force Base in Omaha, Nebraska.

The following excerpt is from the NOAA Office of Satellite Operations Daily News Report on November 3, 2004:

> GOES 12 at 0401Z on November 3: SAR receiver signal strength flagging red high intermittently. Engineers notified. GOES 12 at 0420Z on November 3: SAR receiver signal strength returned to normal for no apparent reason. SAR receiver signal strength will continue to be monitored closely.

3.4 Coordinate Interagency Efforts and Resources; Set Priorities; Ensure Exchange of Information and Plans

The Assessment Committee determined that the same assessment issues were relevant to these three NSWP activities. For the purpose of assessment findings and recommendations, the committee found it more useful to address all three activities together with respect to observing capabilities, forecasting capabilities, and specification capabilities.

3.4.1 Observing Capabilities

The NSWP has as its key data sources a number of important infrastructure elements maintained by the agencies active in space weather pursuits. These infrastructure elements are listed in tables 3-5 and 3-6, which update a similar table compiled in 1995 at the initiation of the NSWP (Tascione and Cliffswallow 1995). To highlight enhancements and deletions in this vital program infrastructure, the tables include the number of operational elements in each program or mission as of 1995 and as of late 2005.

3.4.1.1 Recent Gains in Operational Observing Capabilities

The most important active infrastructure enhancements during the last decade have been the positioning at the L1 Lagrange point of two solar and interplanetary monitors: the Solar and Heliospheric Observatory (SOHO) and the Advanced Composition Explorer (ACE). Data from these science missions are being used operationally and are the key providers of lead-time data in space weather forecasting. SOHO and ACE data, and results derived from these data, permeate current space weather nowcasting and forecasting. These data were identified in the 2000 NSWP Implementation Plan as required sources for four of six NSWP solar-interplanetary metrics. The prediction requirement in that plan cannot be met without an upstream solar wind monitor for comparison (OFCM 2000, pg. 2-24). Similarly, the target architecture level described in the NSSA *Space Weather Architecture Study* cannot be met without an upstream monitor (NSSA 1999, pg. 12; OFCM 2000, pg. C-2).

Among the most important passive infrastructure enhancements has been the development of technologies and algorithms to incorporate ionosphere parameters derived from GPS signals. The widespread use of GPS for space weather monitoring and forecasting was not anticipated in the 1995 Strategic Plan and was mentioned only sparingly in the 2000 Implementation Plan. Future support of these technology and algorithm developments would allow NSWP agencies and participants to take advantage of these new observational capabilities and to support the growing space weather forecast needs in the $20 billion GPS industry.

Another important enhancement of this passive infrastructure has been the effort to recover and predict neutral atmosphere densities from observed drag effects on space debris and inactive orbiting payloads. The DOD recently announced a reduction in density error estimates at 400 km from 16 percent to 10 percent through the use of a Dynamic Calibration Atmosphere to estimate density corrections directly from tracking observations. Most of the improvement has come in the climatological and day-to-day solar EUV forecasts. Geomagnetic storm interval forecasts still

Table 3-5. Space-Based Observation Capabilities for Operations

Program/ Mission	Product	Owner/ Operator	1995 Status[a]	2005 Status	Measurement(s) & Situational Awareness	Comments (*RT*= real time *NRT*=near real time)
Current programs/missions						
	Calibration satellites (inactive)	US DOD		~75	Satellite drag	Daily; input to drag model
POES/	LEO particles	US NOAA	4	4	Particle sensor	*NRT*
DMSP	LEO particles, mag./elec. fields, UV imaging	US DOD/ NOAA	3	3	Particles, plasmas, magnetometer, UV imager	To be replaced by NPOESS
LANL	GEO particles	US	3	2	Geosynchronous particles	Post analysis
GPS	MEO particles	US DOD		> 5	Radiation belt particles	Post analysis
GOES	GEO particles Solar X-rays, fields images	US NOAA	2	2	Solar X-ray and EUV, particles; geomagnetic events	*RT*
ACE	L1 particles & fields	US NASA /NOAA	0	1	Semi Operational Solar Wind Monitor	*RT*. no planned sustainment
SOHO	Solar/coronal images. spectral irradiances	US NASA /ESA	1	1	Science Mission Solar Monitor	*NRT;* no planned sustainment
Future programs/missions						
MetOp	LEO particles	EUMET SAT	2	2	Operational (same as POES)	Launch June 2006
NPOESS	LEO particles, elec. fields, UV imaging	US NOAA /DOD	3	3	Replace POES, DMSP	Launch to be determined; not as capable as DMSP
COSMIC	GPS occultation	Taiwan	4	4	Ionospheric electron density profiles	Launch 2006
STEREO	Solar/coronal images	US NASA	2	2	Solar Science mission	Launch 2006
SDO	Solar images, EUV magnetograms,	US NASA	1	1	Solar science mission	Launch 2008

[a] As reported in Tascione and Cliffswallow 1995.

offer a significant challenge for space weather forecasting and will require multiagency efforts to meet accuracy goals.

3.4.1.2 Near-Term Anticipated Gains in Operational Observing Capabilities

The European MetOp program (first launch in 2006) will improve NOAA/SEC operational products by providing additional polar data obtained with space weather particle sensors of the same design as those now flying on Polar-orbiting Operational Environmental Satellite (POES)

Table 3-6. Ground-Based Observation Capabilities for Operations

Program/ Mission	Product	Owner/ Operator	1995 Status[a]	2005 Status	Measurement(s) & Situational Awareness	Comments (*RT*= real time *NRT*=near real time)
SOON	Solar Optical Network	US DOD	5	3	H-alpha, white light, flares, active regions	*RT;* longitudinal network
	Other telescopes	US	5	> 5	Magnetographs, multi freq, H-alpha,	*RT;* national & internat'l observa-tories via Internet
F10.7	Penticton Radio Observatory	Canada	1	1	Single freq,, 10 cm	*Daily* Single observatory
DISS	Digital ionosondes	US DOD	13	15	Ionosphere parameters	*NRT;* legacy network
	Ionosondes	US, Internat'l		25	Ionosphere parameters	*NRT;* internat'l data exchange
	Ionosondes	Int'l	4	~ 90	Ionosphere parameters	*Post analysis*
IMS	Ionospheric Measuring System	US DOD	0	4	Total electron content and scintillation	Phasing out
SCINDA	Scintillation Network Decision Aid	US DOD		> 12	Equatorial scintillation	*NRT;* operated with internat'l partners
	Polarimeters	US DOD	4	0	Plasma irregularities	Phased out
Riometers	Relative ionosphere opacity meters	US	8	2	Polar cap absorption	*RT;* other internat'l networks available via Internet
GPS	Ground receiver stations	US		50	Total electron content	*NRT;* various net–works and cadence
GPS	Ground receiver stations	US, internat'l		> 125	Total electron content	*NRT;* expanded coverage & cadence; post analysis
USGS	Ground magnetometers	US	13	13	Geomagnetic Indices	*RT n*orthern hemisphere network
Other	Ground magnetometers	US, Internat'l	7	~150	Storm studies, index development	*Some RT, post analysis*

[a] As reported in Tascione and Cliffswallow 1995.

spacecraft. These data will improve the 'refresh rate' for POES products. The planned National Polar-Orbiting Operational Environmental Satellite System (NPOESS) will be a further improvement over POES and is expected to provide good space weather data. The next generation of GOES spacecraft (launch in 2006) will have a solar extreme ultraviolet (EUV) sensor, which will enable enhancement of the ionosphere and thermosphere models, especially those for satellite drag.

New research satellites will include Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC). Its fleet of GPS sensors for occultation observations will provide global electron density profiles. Solar Terrestrial Relations Observatory (STEREO), with its coronagraphs and solar-wind monitors, will provide predictions of coronal mass ejections (CMEs). There is a good chance that COSMIC and STEREO will be used operationally at some point. Other research satellites include the Solar Dynamics Observatory (SDO), which will provide excellent solar UV images, magnetograms, and EUV spectra.

3.4.1.3 Near-Term Anticipated Losses in Operational Observational Capabilities

The NPOESS program will not provide the same space weather capabilities now available on Defense Meteorological Satellite Program (DMSP) satellites. A DMSP satellite has both a limb-view and nadir-view UV sensor. An NPOESS spacecraft will have only a nadir-viewing UV sensor. This difference will impact two key parameters: the electron density profiles and the neutral density profiles.

The most significant impact to space weather operations would result from the loss of ACE monitoring capabilities. This spacecraft at L1 provides essential advanced warnings and information used in numerous space weather prediction models, as well as in the SEC forecast center. Without ACE, the forecast centers will lose the capability to provide accurate predictions for numerous products. There is currently no plan to replace ACE, although China has announced plans for a similar spacecraft at L1. NOAA is currently supporting studies to evaluate possibilities for a follow-on capability at L1.

The SOHO coronagraph represents a critical solar monitoring capability. If it should eventually fail before a replacement is in place, its absence would materially degrade operational space weather forecasts. SOHO provides a unique view of, and advance warning about, potential space weather storms. STEREO will provide important data for an interval after its launch (summer 2006), but its orbit will inevitably move it from its most useful orbital position for space weather operational use.

3.4.2 Forecasting Capabilities

Table 3-7 illustrates warning, prediction, and analysis capabilities in each space weather regime as they were assessed in the 2000 NSWP Implementation Plan. Red indicates no capability to meet the requirements for the events in the given region, red/yellow (Red Yel) indicates very limited capability, and yellow (Yel) indicates some capability short of meeting operational requirements. No areas are coded green (capable of meeting requirements) because user-specified needs could not be met.

The following paragraphs, quoted from the 2000 Implementation Plan, summarize capabilities at that time in the four product areas of space weather warnings, nowcasts, forecasts, and post analysis.

> *Warnings.* Very little capability exists to warn for space weather events. Causal solar events can be detected in real time, but warnings based on these events lack sufficient reliability for immediate mitigation actions and do not provide useful lead time or information on magnitude and duration of the event.
>
> *Nowcasts.* Limited nowcasting capability based on rudimentary models exists at operational centers. However, the models offer little capability beyond information available from empirical methods and climatology. Capability is best when data to initialize the models are received in a timely manner.

Table 3-7. 2000 Implementation Plan Assessment of Capabilities to Meet Warning, Prediction, and Analysis Requirements[a]

	Warning		Nowcast		Forecast		Post Analysis	
Solar/Interplanetary	Red	Yel	Red	Yel	Red	Yel	Yel	
Magnetosphere	Red		Red	Yel	Red		Red	Yel
Ionosphere	Red		Red	Yel	Red		Yel	
Neutral Atmosphere	Red		Red	Yel	Red		Red	Yel

[a] Source: OFCM 2000, table 2-1, page 2-14.

> *Forecasts.* Forecasting capability suffers from the same weaknesses as warning capability, and, in addition, the challenge is greater because forecasting requires longer lead times. This in turn requires a more complete understanding of both the solar events that drive space weather and the way the space environment reacts to those events.
>
> *Post-Analyses.* Current capabilities are the strongest in support of post-analysis requirements; however, significant deficiencies still exist. The relatively strong capability in this area derives from the fact that some post-analyses are not required in real time. This allows the analyst to gather data that may not have been immediately available to operators and to assimilate it at leisure.
>
> In summary, these limited capabilities come from a basic understanding of space weather combined with a limited observation base and still rudimentary computer models. However, they lack the necessary accuracy and four-dimensional detail to meet operational requirements.
>
> (OFCM 2000, pg. 2-14)

Table 3-8 illustrates the best estimates for the status of capabilities to meet requirements in these same four product areas, using the same color codes as for table 3-7. There have clearly been some improvements in some areas over the past half-decade. There are, however, still no green boxes. The next four paragraphs provide the basis for these assessments.

Table 3-8. Assessment of Warning, Prediction, and Analysis Capabilities in 2005[a]

	Warning		Nowcast		Forecast		Post Analysis	
Solar/Interplanetary	Red	Yel	Red	Yel	Red	Yel	Yellow	
Magnetosphere	Red	Yel	Red	Yel	Red		Red	Yel
Ionosphere	Red	Yel	Red	Yel	Red		Yellow	
Neutral Atmosphere	Red	Yel	Red	Yel	Red	Yel	Yellow	

[a] Estimates by the NSWP Assessment Committee of status as of late 2005, based on 2005 requirements.

Warnings in 2005. Ordinary solar event occurrences can be detected in real time. With the positioning of spacecraft at L1 and advances in modeling capabilities, some space weather warning requirements are being met. ACE data generally provide a 1-hour lead time for the onset of geomagnetic storms. Data on energetic particles sensed at L1 provide some warning of rising fluxes of such particles due to interplanetary disturbances. Rising energetic particle fluxes are also monitored by NOAA GOES spacecraft and DOE and other satellites in geosynchronous orbit.

Nowcasts in 2005. The SEC introduced the NOAA space weather scales for geomagnetic storms, radiation storms, and radio blackouts from ionospheric storms. In addition, interested parties can view text or graphic displays from five model outputs at http://www.sec.noaa.gov using pull-down menus. Tailored products are becoming available from both SEC and the DOD for specific customer needs. Most models are still empirically based, but some parameterized, partial physics-based models are coming on line. Timely data access often remains a weak link in the nowcasting process.

Forecasts in 2005. Forecasting capability is just beginning to make strides. If transition resources are sufficient, the lag from major model inception to rudimentary forecasting capabilities appears to be roughly 5 years. However, as discussed elsewhere in this report, lack of adequate transition resources has hindered progress in NSWP operational forecasting capability.

Post-Analyses in 2005. National capabilities are strongest for post-analysis products. The dominant work in this area is by the academic community, with contributions from some agency laboratories, such as NASA centers, AFRL, and DOE's Los Alamos National Laboratory (LANL). NSF and NASA have supported a number of specific retrospective studies via various campaign programs and studies including International Solar-Terrestrial Physics Project (ISTP), Geospace Environment Modeling (GEM), Coupling, Energetics and Dynamics of Atmospheric Regions (CEDAR) and Solar and Heliospheric Interplanetary Environment (SHINE). The operational centers also perform assessments of major storms as customer needs and time dictate.

3.4.3 Specification Capabilities

NASA and the DOD have supported space radiation specification tools that are being adapted for use in Earth's atmosphere. The FAA has its own radiation code, CARI-6, that calculates the effective dose of galactic cosmic radiation received by an individual on an aircraft flying a great circle route between any two airports in the world. The program takes into account changes in altitude and geographic location during the course of a flight, as derived from the flight profile entered by the user. Similar model developments are being pursued in Europe and Canada to describe the radiation environment for high altitude flights and long-haul tropospheric flights. Some international airlines monitor radiation dose for specified routes and for flight crew members.

> ***Finding 3.2.*** The FAA Air Traffic Organization's advisory *User Needs Analysis* identifies biological radiation exposure as a specification and prediction issue. The FAA Civil Aeromedical Institute has a rudimentary interface for public use available on the internet.
>
> ***Recommendation 3.2.1.*** The NSWP should encourage and facilitate collection and analysis of real-time background radiation levels at space and aircraft altitudes. As a body, the NSWP should devote interagency resources to

incorporate estimated dosage from energetic particle events into cosmic radiation exposure estimates and to make the specifications and results easily accessible, usable, and interpretable by the public via the Internet.

3.4.4 Assessing Capabilities with Metrics

The Assessment Committee received little data comparing performance to the metrics outlined in the NSWP 2000 Implementation Plan. Such information was proffered neither by the individual Agencies nor in the Committee on Space Weather briefings of the Assessment Committee.

> ***Finding 3.3.*** Little information was available on program performance as related to the metrics given in the latest (2000) NSWP Implementation Plan.

3.4.5 Agency Versus Interagency Efforts and Resources

The various infrastructure, warning, prediction, and analysis elements listed in tables 3-5 to 3-8 are largely the result of the actions and decisions—and thus priority setting—of individual agencies, although information is provided to the other agencies through the auspices of the Committee on Space Weather. Because of this loose confederation approach to participation in the NSWP, significant and progress-inhibiting gaps often occur in overall NSWP planning, coordination, role-determination, and priority-setting. Such gaps are most apparent in the realms of program metrics and programs that require interagency agreement on major spending. The consequences of these gaps are particularly noticeable for planning and budgeting and for solar and interplanetary monitors.

> ***Finding 3.4.*** The National Space Weather Program Council does not have the authority to mandate roles, responsibilities, or priorities for space weather infrastructure needs. Nor can it allocate resources.

These needs are still largely addressed by individual agencies to the detriment of a truly national program.

Space Weather in Department of Defense Operations

The three anecdotal examples presented here of space weather impacts on DOD operations demonstrate two points: First, the infusion of space weather support to DOD operators can have a positive impact on operations. Second, a great deal of customer education in space weather remains to be done; often the operator is unaware when space weather is the cause of a problem. All three of these problems were encountered within the past 1–5 years.

- High Frequency (HF) radio operations are often impaired during active flare events for regions located on the sunlit side of the Earth, particularly near the subsolar point. Forecasters in the Air Force Space Weather Operations Center (SWOC) produce warning bulletins for these short-wave fade events and then usually contact HF centers near the subsolar point to confirm loss or degradation of HF communications. During one such event, the forecaster contacted the center in Hawaii and requested a communication check with Yokota, Japan. The radio operator returned to the phone reporting Yokota was heard "loud and clear." The stunned forecaster asked what frequency the operator used and was told: "Oh, I couldn't get him on the radio, so I called him on the phone."

- A deployed team was trying to conduct a daily briefing using satellite communications each day at 2100L (9:00 pm local). Due to constant communication issues, the team struggled each day to conduct these briefings. When a weather forecaster (who had a background in space weather) deployed with the team, he quickly determined that the cause of the problem was ionosphere scintillation. With this key piece of information, the deployed team was able to work their briefing times to avoid scintillation effects.

- Radio operators in Thule, Greenland, were having strange multi-day radio outages that were attributed to equipment maintenance issues. Maintainers would spend days pulling radios apart, never being able to determine the cause. The Thule unit then began receiving space weather support and discovered that polar cap absorption events were the cause of the long-term radio outages and had nothing to do with the performance of the radios themselves. Infusion of space weather support saved many hours of fruitless maintenance support.

3.5 Encourage and Focus Research

Research has sustained the NSWP effort during the past 10 years. Agencies under the NSWP umbrella successfully seeded a number of research initiatives. These initiatives have two forms: *targeted* research and *strategic* research. Distinctions between the two types of research are sometimes difficult to draw definitively. "Targeted research" as used here denotes research that is aimed at specific and immediate space weather–related problems. "Strategic research" denotes a planned research effort that addresses broader physical and process issues in space weather. Tackling strategic issues typically requires crossing agency boundaries and coordinating agency funding. New research funding may be necessary.

As discussed below, a burst of targeted research activity arose in the FY 2000 time frame. The sustainability into the future of such targeted research is unclear at the present time. A planned, synergistic approach to research at the multi-agency level will probably be required to sustain future efforts.

3.5.1 Targeted Research

3.5.1.1 National Science Foundation

During the past 10 years, NSF has been an extraordinarily effective catalyst for individual, institutional, and interagency research. A new annual competition for proposals within the Upper Atmosphere Research Section (UARS) created an additional funding opportunity for individuals and teams focusing on observational and predictive research in space weather as a system. Although NSF does not fund transition-to-operations activities, UARS has actively supported verification and metric comparison projects at NASA's Community Coordinated Modeling Center (CCMC). UARS also funds operations at several major ground observatories that contribute to space weather research. Development of the Advanced Modular Incoherent Scatter Radar (AMISR), a major new ground-based facility for studying space weather and characterizing ionosphere-magnetosphere coupling, is the fruit of UARS-supported research facilities. The NSF-funded Synoptic Optical Long-term Investigation of the Sun (SOLIS) is currently providing full-disk and high-resolution line-of-sight magnetograms on a daily basis.

With support and consultation from UARS, NSF invested in a major National Science and Technology Center, the Center for Integrated Space Weather Modeling (CISM). This is a 5-year (with possibility for a 5-year renewal), multimillion dollar effort to understand and model the dynamic Sun-Earth system. The goal is to create a physics-based numerical simulation model that describes the space environment from the Sun to the Earth. CISM's modular approach allows individual researchers to insert promising new empirical or physics-based modules as they are developed.

3.5.1.2 Department of Defense

Funding by the DOD for targeted research has had strong justification from specific users. During the past 5 years, the DOD has invested heavily in modeling and forecasting efforts via a funding tool known as a Multidisciplinary University Research Initiative (MURI).

There have been three DOD-sponsored MURIs in targeted space weather research. The first, a Space Weather MURI awarded to the Center for Space Environmental Modeling (CSEM) at the University of Michigan, was focused on modeling and predicting solar eruptive events and their effects on space weather. Some elements of the CSEM MURI are now undergoing evaluation at the CCMC. This Space Weather MURI is closely coordinated with its sister effort, the Solar MURI, coordinated by the University of California, Berkeley. Utah State University (USU) and University of Southern California (USC) participated in a third MURI for assimilation of ionospheric data. As a result, the USU Global Assimilation of Ionospheric Measurements (GAIM) model is transitioning to operations at AFWA in 2006. Validation has been supported by AFRL. At present, no further MURIs have been identified.

The Office of Naval Research has supported targeted research in:

- Solar coronagraphs and solar wind monitoring
- Improved ionosphere specification and forecast, including initiatives such as GAIM and imaging from geosynchronous orbit
- Ultraviolet remote sensing of the thermosphere and ionosphere
- Low-cost, quick-launch vehicles.

The Large Angle and Spectrometric Coronagraph (LASCO), developed by a consortium led by the Naval Research Laboratory (NRL) as an instrument on the joint NASA-ESA SOHO mission, has been returning images of the Sun's atmosphere from L1 since its launch in December 1995. NRL continues to be active in sensor development. It's contributions to future space weather missions include three different coronagraphs and an EUV imager on two independent spacecraft for the NASA STEREO mission, as well as a high-resolution spectrometer to be flown on the Japanese Solar-B mission.

The Air Force has led the effort to develop operational nowcast and forecast improvements for the neutral atmosphere with a project that incorporates the Dynamic Calibration Atmosphere along with a substantially revised empirical thermospheric density model.

The Space Weather Center of Excellence in the AFRL Space Vehicles Directorate supports both in-house and contracted research in:

- Development of empirical, assimilative, and/or physics-based models to fill gaps in sensor coverage
- Physics-based and quasi-empirical models for high-priority forecast regimes
- Improved design tools and exploration of active techniques to improve and extend the lifetimes of systems subject to space weather damage
- Ground-based and space-based sensors to feed data-starved specification models.

An example of AFRL-sponsored research that has transitioned to operations is the Scintillation Network Decision Aid (SCINDA)—a ground-based sensor and computer model system that specifies and forecasts satellite communication outages caused by ionospheric scintillation.

Recent AFRL initiatives include the Solar Mass Ejection Imager (SMEI) satellite mission, which has been on orbit since 2003. To date, hundreds of CMEs have been catalogued for study. Substantially more analyses and publication of these data would be very worthwhile for basic solar and interplanetary research, as well as for space weather purposes.

AFRL scientists have developed a new application of the satellite magnetometer data from the DMSP system to aid in forecasting extreme upper-atmosphere heating events. Such events are likely to create excess drag on satellites in low Earth orbit (LEO), resulting in loss of precision satellite orientation, as well as a significantly degraded ability to track satellites and other objects in LEO.

The DOD's space weather research effort at AFRL has been compromised at times. Program funding cuts, patchwork-like tasking from multiple user organizations, and customer-funded research have, in essence, created a bimodal distribution of efforts in basic research and advanced technology development at the expense of applied research. As a result, efforts in model transition, ground-based instrument fielding, and space-based instrument development have stretched into decade-long time frames.

Long-term funding for DOD space weather research activities appears to be in decline. Despite recommendations for a "robust space weather research and development program" from the 1999 NSSA *Space Weather Architecture Study* (see Appendix E), there appears to be no coherent plan for long-term space weather research funding and/or prioritization at the DOD executive agent level (NSSA 1999, pg. 10). Further, a significant fraction of the AFRL space weather work force will be eligible for retirement over the next 5 years.

3.5.1.3 Department of Energy

LANL is working on a targeted program to assimilate radiation belt data into a Dynamic Radiation Environment Assimilation Model (DREAM). The effort focuses on understanding natural and artificial processes in the radiation belts. (See the sidebar box "Nuclear Weapon Effects and the Space Environment" at the end of section 3.5.)

3.5.1.4 Department of the Interior

USGS investigators conduct limited research, consistent with budget constraints, on new uses and applications of ground magnetometer data. These data are used for the construction of geomagnetic indexes to assess the space weather state of the ionosphere and magnetosphere. The data provide important backup capability for situational awareness of the geomagnetic environment in the event of a data outage from space assets at L1.

3.5.1.5 Department of Commerce

The NOAA/NWS presentation to the Assessment Committee indicated that the transition of the SEC to operational status within NCEP could reduce SEC targeted research activities—activities that lead to new forecast products and services. In particular, two important research activities appear to be at risk:

- Understand the processes that influence space weather and develop applications for the user community
- Develop new and improved products and transition them into operations to meet evolving users' space weather needs.

It is not clear how NOAA will address this situation.

3.5.1.6 National Aeronautics and Space Administration

NASA space weather research contributions are in two primary areas: (1) Living With a Star (LWS), an initiative focused on space weather and the space environment, and (2) space hardware already on orbit. LWS could also be considered in the strategic research category in that many elements of this program address issues that can affect NASA space systems and future programs, including human exploration.

The primary objective of the LWS program is to perform investigations in space to understand solar variability and its effects at Earth, leading to a capability for reliable prediction of solar variability (i.e., space weather). LWS has three major program elements: Spacecraft, Space Environment Test beds, and Targeted Research and Technology (TR&T) grants.

- The LWS-supported Solar Dynamics Observatory (SDO) is scheduled for launch in 2008. Proposals for the Radiation Belt Storm Probes (RBSP) are under review, and the program may slip somewhat due to decreases in the LWS program budget. The Ionosphere Storm Probes (ISP) are currently delayed for almost a decade, even though the NRC's Decadal Research Strategy in Solar and Space Physics (NRC 2002) envisioned ISP as comprising, with RBSP, a comprehensive system for investigating the Earth's space environment.
- The Space Environment Test beds Project is the element of LWS intended to characterize the space environment and its impact on hardware performance in space.
- NASA has formed focused research teams to tackle problems of pressing concern within the overall TR&T program. The aim of TR&T is to provide a physics-based understanding of the Sun-Earth system. In addition to research topics associated with NSWP activities, LWS research topics include analysis of energetic particles that pose a hazard to astronauts or technology and analysis of the effects of solar variations on Earth's climate.

In 2006, NSF and NASA are jointly administering a basic research grants program focused on high-priority needs in space weather modeling. This joint activity will provide the research community with about $1.5 million of support for focused space weather modeling. Similarly, a joint NSF-NASA program is funding the Global Oscillation Network Group (GONG) to provide real-time line-of-sight solar magnetograms and far-side solar imaging.

Space hardware already on orbit continues to make important and critical contributions to space weather research, as well as to operations. The ACE and SOHO satellites are the most compelling examples of critical contributions to applicable space weather objectives. Many essential space weather forecast products rely on data from these research satellites. Yet, as shown in table 3-9, more than half of the currently flying research missions of importance for space weather data are scheduled for termination by 2011.

Table 3-9. Operating NASA Science Missions

NASA Mission	Launch	Mission End	Organization	Comments
IMAGE	2000	December 2005[a]	GSFC	
Polar	1996	Mar 2007	GSFC	Fuel Depleting
Ulysses	1990	Mar 2008	JPL	Begin 3rd Pass over Sun
FAST	1996	July 2008	GSFC	
Geotail	1992	July 2008	GSFC	
TRACE	1998	Nov 2008	GSFC	
Cluster	2000	~ 2010	GSFC	
ACE	1997	> 2011	GSFC	
RHESSI	2002	> 2011	GSFC	
SOHO	1995	> 2011	GSFC	
TIMED	2001	> 2011	GSFC	
VOYAGER 1 & 2	1997	> 2011	Cal Tech	V1 - 99 AU, V2 – 80 AU
Wind	1994	> 2011	GSFC	
SAMPEX	1992	TBD	GSFC	Mission extended via multi-agency agreement

[a] IMAGE failed in orbit in mid-December 2005.

3.5.2 Science and Operational Data Sources

From the review in section 3.5.1, it is clear that much of the data essential for observing and predicting space weather for both civil and national security systems are presently obtainable only from scientific research satellites such as ACE and SOHO. Many other in situ space weather data are also obtained from primarily science-driven satellite programs (e.g., TIMED, Polar). Major exceptions to this reliance on research spacecraft are the geosynchronous energetic particle data that are acquired under the auspices of the DOE; the particle, magnetic field, and solar x-ray data from NOAA's GOES and POES spacecraft; and the DOD's DMSP spacecraft. While individuals in relevant agencies recognize the often ad hoc nature of the data sources for space weather applications, the Assessment Committee found no active planning for specific space weather missions that would provide the data required for continuation of many important space environment monitoring and prediction programs.

Even given the recognized ad hoc nature of the critical data sources, there appears to be far too little discussion among the agencies in the NSWP as to the prioritization of the data types and sources that are required for space weather research and for operational applications. This situation leads to too little planning for contingencies in the event that some data (space- or ground-based) become unavailable for whatever reason. In the case of science missions that are at or beyond their design lifetimes (see table 3-9 above), the committee could discern little interagency strategic planning for replacement data sources when service life finally ends, whether suddenly or gradually over some time interval.

Many ground-based data that are used for determining geomagnetic activity and ionosphere parameters (e.g., magnetometers, ionosondes, GPS receivers) are acquired for other than space weather applications. To obtain the necessary global data coverage, many of the data sources are, of necessity, foreign. The future reliability of such sources, and therefore their supply for their use for national interests, is not sufficiently well understood. While officials express concern about the loss of data from such sources, there does not appear to be any planning for possible back-up alternatives (if indeed any alternative sources are available).

> ***Finding 3.5.*** Many data sets that are critical for both civilian and national security elements of the NSWP are obtained from science programs of often limited duration (some of these sources are already beyond their design lifetimes) or from sources originally designed for other objectives. Relatively little discussion and contingency planning are underway as to how the NSWP will incorporate possible foreign sources of critical space weather data if some national data sources become unavailable.

Many instruments designed as data sources for operational space weather applications need not achieve the high precision of measurements usually required for scientific research objectives. Measuring to within 20 percent (or perhaps with even less precision) is generally good enough. Such loosening of requirements means a significant reduction of costs. Of particular promise for carrying affordable space weather instrumentation is the new class of “micro-satellites.” These systems weigh some 50-200 kilograms and cost on the order of $10–$30 million to construct and launch. The Student Nitric Oxide Explorer (SNOE) satellite, built and operated for more than 6 years at the University of Colorado for less than $5 million, produced a large and unique data set that is important for several problems in space weather. Slightly larger mini-satellites weighing about 500 kg have also been built for very low cost. (See the sidebar box “Micro-Satellites and Space Weather” following section 3.6 below.)

Until recently most micro-satellites have been launched into LEO, but this is changing. Moreover, most successful micro-satellites have been European developments. The Space Technology Centre at the University of Surrey (U.K.), a leading European developer of micro-satellites, has been building lightweight, low-cost satellites for more than 20 years. The University of Surrey recently successfully built and launched the prototype for Galileo, the European global positioning system. The cost of this high-orbit satellite was $30-$40 million. Recent progress by the DOD, DOE, and NASA has shown that U.S. capabilities in this low-cost area are growing as well.

> ***Recommendation 3.5.1.*** The cooperating agencies in the NSWP should investigate immediately the feasibility of using micro-satellites with miniaturized sensors to provide cost-effective science and operational data sources for space weather applications.

A major policy decision will face the NSWP if, for example, the only L1 data available at some point in the future were to be those supplied by another country, especially if such data were critical for applications and predictions, as ACE data are currently. Some other space-faring nations appear to be considering the acquisition of data useful for space weather warnings and prediction. For example, China may be planning an L1 spacecraft that could provide interplanetary data similar to those now acquired by ACE. Similarly, if some of the geomagnetic or ionospheric data that are currently acquired from other nations were suddenly denied to U.S. users, civil and national security monitoring and prediction activities would face a difficult situation.

> ***Finding 3.6.*** It is particularly critical to ensure continuity of space weather observations at L1 and continuity in delivery of that data in near real time. Planning for continuity is necessary prior to the failure of current scientific instruments at L1.
>
> > ***Recommendation 3.6.1.*** Micro-satellites and other small missions should be seriously pursued as an option for providing continuity of critical space weather data from observations at L1.

Retrospective data from data centers can serve as invaluable sources for the examination of past events of space weather importance and for reexamination of solar-terrestrial space weather patterns in the context of new scientific understandings, even years after the observations are made. Important data centers in this regard are the NOAA National Geophysical Data Center and the NASA National Space Science Data Center. Both provide invaluable data archiving and access to past data sets.

The Decadal Research Strategy in Solar and Space Physics stated that engineers are typically interested in space climate, rather than space weather, when designing ground- and space-based systems. The goal of designers is to design a system to be immune to space weather effects as much as is feasible. For design purposes, "the space environment should be removed from the equation; any further space weather issues that might arise can be dealt with separately." To do this, designers need long-term averages of space weather phenomena, the uncertainties in these averages, and values for extreme conditions (NRC 2002, pp. 15, 123).

The NSSA *Space Weather Architecture Study* also stressed the importance of a space weather information archive. It recommended consolidating and expanding the existing archival system to capture space weather environmental data and systems impacts (NSSA 1999, pg. 14).

Data centers can be invaluable in providing retrospective data that can be analyzed and used for space weather climatology studies and model building. However, as the Decadal Research Strategy noted, when climatology models of the space weather environment are developed, extreme conditions tend to be either ignored or not properly represented. The reason for this tendency may be that too few data points exist to justify including them in a statistical database (NRC 2002, pg. 123).

The Decadal Research Strategy concluded that designing for space weather conditions could be considerably enhanced if a centralized database of past extreme space weather conditions existed. The authors recommended that such a database be established. It should cover as many relevant space weather parameters as possible. A possible location for such a database could be within either NOAA/SEC or NOAA's National Geophysical Data Center (NRC 2002, pp. 15, 123).

3.5.3 Strategic Research

All agencies that participate in the National Space Weather Program Council (NSWPC) have strategic research components in support of their own agency's goals. These strategic components can be the ones most likely to suffer reductions in times of tight budgets. This is a serious concern because strategic research initiatives create the pool of knowledge from which focused applications are developed.

There is a lack of strategic research planning at the NSWPC level. For example, users have identified the lack of in situ thermospheric and ionospheric measurements as a significant data and knowledge gap that inhibits the development of several space weather applications. There currently appear to be no plans for new capabilities in these critical areas until 2015 or beyond. Some space weather data sources may also be lacking in the future because cost overruns in the NPOESS program may necessitate elimination of some instrumentation.

Strategic research is closely related to the level of space situational awareness that may – or may not – exist in the relevant agencies at a given time and over major planning cycles. It is very important that the senior leadership in agencies with space weather–related responsibilities have a good working knowledge of space environmental impacts, as well as the knowledge of the research required to address these impacts. Of particular concern to the Assessment Committee is the status of strategic research in two agencies—the DOD and the DOE.

3.5.3.1 Department of Defense

Strategic research is particularly important for the DOD because the military services anticipate greatly increased reliance on space systems in the decades ahead. Recognizing this importance, the DOD in concert with the National Reconnaissance Office (NRO) initiated a Space Weather Architecture study in 1998. The study was conducted by the NSSA, which had been charged with conducting analyses across the entire range of national security space interests. The key findings and recommendations from the study (NSSA 1999) are summarized in Appendix E. While the national security community has made progress on some of the NSSA recommendations, others have not progressed—particularly the recommendations on strategic research and planning.

The first area of NSSA focus was general space architecture development. The NSSA study recommended emphasis on operational model development. Considerable progress has been made by DOD in the MURIs noted earlier. However, the DOD has been less successful in translating and transferring this understanding into operationally useful prediction and procedures, largely due to insufficient resources and to reductions in the number of professionals trained in space weather.

The NSSA recommended a vigorous effort in space weather importance awareness. In discussions with operational commands, the Assessment Committee found that, while individuals understand the import of space weather, little progress has been made command-wide in this important area. Relegation of space weather to non-space-oriented organizations appears to have contributed to this problem.

The NSSA recommended the identification of a central cognizant organization within DOD to oversee space weather. It appears that such an organization does not exist, although the NSSA's successor organization, the National Security Space Office, may be the appropriate location for such a function.

The NSSA study made recommendations concerning a central space weather information archive (NSSA 1999, pg. 14). NOAA's National Geophysical Data Center, AFWA, and the AFSPC Space Situation Awareness Information Office each have portions of such an archive. It is not clear, however, that these portions are connected in any meaningful way. This situation hampers the DOD's ability to respond to the NSSA recommendations on central requirements development and user information. The matrix of organizations that currently exists appears disconnected from the top-level coordination functions recommended in the NSSA study.

An area of increasing focus for the DOD was covered in the NSSA recommendations on space weather and man-made effects. The study recommended that the DOD:

- Support the Space Control Protection Mission by providing timely space weather information
- Incorporate the operational specification and forecasting of space environmental effects of man-made (primarily nuclear) events (MME) as a mission into the space weather architecture (NSSA 1999, pg. 18).

Although they recognize that space weather is part of the top-priority space situation mission, the DOD's operational elements do not appear to have connected space weather in a cohesive way to the MME mission area. In contrast, DOD research organizations have embarked on a focused effort to mitigate the damaging and potentially catastrophic effects of a radiation belt pumped up by a nuclear explosion. This research area, Radiation Belt Remediation (RBR), depends critically on accurate space weather understanding and prediction. (See sidebar box "Nuclear Weapon Effects and the Space Environment" at the end of section 3.5.) It does not appear that the DOD has fully made the connection between RBR and space weather. Leadership in such matters can only come from the senior leadership in the relevant agencies.

3.5.3.2 Department of the Interior

Similarly, but in a different realm—on the Earth's surface—the USGS National Geomagnetism Program provides important inputs into many critical NSWP products. Yet it appears that the importance of (and the necessary resources for, including some funding for strategic research) the geomagnetism program is not appreciated even by many within the space weather community, let alone by national and agency leaders.

3.5.3.3 Summary on Strategic Research

While the NSWP must certainly stress the importance of space situational awareness to critical national interests and the impacts and potential consequences of space environmental activity on these interests, it is also important that the program not devolve into sensationalism. Space weather impacts could be severe in some cases, including the loss of some satellite-provided services, communications, and even power grids. It is unlikely, however, that the average citizen will experience or suffer a space weather event that would have devastating consequences comparable to the recent hurricane or tsunami damage. As noted earlier in this chapter, comprehensive and rigorous strategic research and impact analysis of likely and possible impacts (including cost impacts) do not exist at present for space weather, but they are needed.

> ***Finding 3.7.*** The benefits of having space weather strategic research and space situational awareness must be more meaningfully assessed and promulgated.
>
> > ***Recommendation 3.7.1***. The NSWP must enhance its efforts to educate the U.S. Government, wider technical communities, and the public on the importance of strategic research and space situation awareness to national interests, particularly about the possible consequences of space weather events for national interests.

Nuclear Weapon Effects and the Space Environment

On June 19, 1962, the United States detonated its first nuclear explosion in space, code-named Starfish. The 1.4-megaton explosion at an altitude of 400 km produced beta particles (electrons) that were injected into the Earth's magnetic field, where they formed an artificial radiation belt. This artificial electron belt lasted until the early 1970s. The first failure (in one of a redundant pair of command lines) on the Telstar 1® communications satellite, which was launched the day after the Starfish explosion, occurred within about 2 months of launch. The radiation produced by Starfish destroyed seven satellites within 7 months, primarily from damage to their solar cells.

The interaction of nuclear detonations with the space environment is of significant concern for at least two U.S. Government agencies: the DOD and the DOE. The DOD relies on dozens of space systems for critical combat support. A Starfish-type scenario could potentially destroy much national security space infrastructure. The DOE maintains a large constellation of space sensors designed to detect and characterize nuclear explosions. While the DOD seeks to mitigate changes to the space environment, DOE wants to understand the complex interactions of nuclear explosions and the space environment in order to better detect and characterize possible new entrants into the nuclear weapons arena.

The Defense Advanced Research Projects Agency (DARPA) in the DOD has begun, in concert with AFRL, an ambitious program to mitigate the effects of radiation injection into the radiation belts. In essence, the research seeks methods to remove trapped particles. This must begin with a precise and thorough understanding of the radiation belts and their current configuration. Low-frequency radio waves injected into the belts might be able to change the trapped population so as to quickly precipitate out the damaging particles (see figure below).

The DOE also seeks a detailed understanding of the radiation belts and their current configuration. From this understanding, the DOE can use the measurements acquired by its space sensors to pinpoint nuclear weapons activity that occurs in or above the atmosphere. This detection capability is a central element of the Nation’s nuclear nonproliferation strategy. LANL is developing a sophisticated, linked model called Dynamic Radiation Environment Assimilation Model (DREAM) as a central tool for this effort.

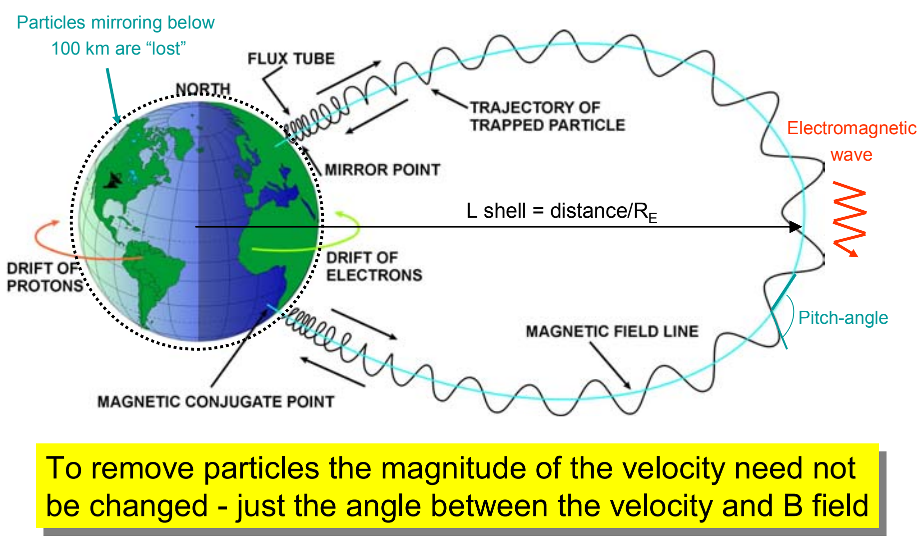

Figure 3-4. Mitigating the effects of nuclear explosions on Earth’s radiation belts. DOD’s Radiation Belt Remediation program seeks to remove high-energy particles from the radiation belts by using low-frequency radio waves to change the pitch angles of the trapped particles. This process lowers the particle mirror points to greatly increase energetic particle losses through their collisions with the atmosphere.

3.6 Facilitate Transition of Research Results Into Operations

Both empirical and physics-based modeling have advanced significantly since the inception of the NSWP. A vision for "technology transfer" of information, data, and models existed when the NSWP began in 1995, and the 2000 Implementation Plan identified three primary transition paths: the Community Coordinated Modeling Center (CCMC) and two Rapid Prototyping Centers (RPCs): one at NOAA/SEC, the other within the DOD (OFCM 2000, pp. ES-4, 2-25 to 2-27).

At the operational level, the "….well-planned and well-executed technology transfer" envisioned in both the 1995 Strategic Plan and the 2000 Implementation Plan (OFCM 2000, pg. 2-25) has yet to materialize. Transition of data, models, and applications into operations has suffered from serious resource deficiencies and appears to follow a tortuous path that wastes resources and slows the expected use of new information and models.

3.6.1 Community Coordinated Modeling Center

Within the transition-to-operations paradigm, the CCMC provides model access and validation leading to comparison with community-designed metrics. As of early 2006, the CCMC is exercising 19 models, including 2 real-time simulations. Experience with and critiques of these models feed back to the model developers. The models being exercised are in the following classes:

- Solar—four models, two of which are physics-based
- Heliosphere—four models, two of which are physics-based; one incorporates data assimilation
- Magnetosphere—six models, four of which are physics-based
- Ionosphere—five models, four or which are physics-based; one is statistical

Five of these models have completed initial metric studies.

3.6.2 National Oceanic and Atmospheric Administration

NOAA/SEC has established a dedicated workspace for transition activities, but the activity is currently resource-constrained. Approximately 5 percent of SEC staffing is currently allocated to transition activities.

Two recent transitions are contributing, or approved for contribution, to the SEC operational baseline:

- SOLAR2000 E10.7 radiation flux model (also under further development for applications at AFSPC)
- Aviation web page.

Six new models are currently running on SEC development computers for test and evaluation to determine their suitability as candidates for transition:

- U.S. TEC Model (Total Electron Content over the United States)
- Solar wind propagation model
- Magnetopause model—predicts location, shape, and variations
- AP forecast model—predicts a geomagnetic index
- Polar cap high-frequency propagation model
- Regional magnetic disturbance model.

The eventual transition to operations of these models, as well as of models that become available in the future, will depend upon the availability of resources.

3.6.3 Department of Defense

DOD model transition activities appear to be divided among AFRL, NRL, elements of AFSPC, AFWA, the DOD-funded MURIs in space weather, and teams within the University Partnering for Operational Support (UPOS) collaboration. Whether a matrixed system such as this can efficiently and rapidly transition models remains to be determined.

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Recent transitions are contributing to the AFWA/SWOC operational baseline:

- Operational Space Environment Network Display (OpSEND) and SCINDA
- Magnetosphere Specification and Forecast model (an inner magnetosphere model)
- Improved Real-Time Kp Estimate and Auroral Boundary Specification and Nowcast
- Relativistic Electron Prediction (produces a 27-day forecast for geostationary satellites)
- Solar wind and interplanetary shock propagation model
- GAIM model (scheduled for operational capability in 2006).

OpSEND is a radio propagation, navigation, and communications tool. The OpSEND team received the Air Force Merewether Award in 2001 for the most significant technical contribution to the air and space weather mission.

A recent transition that is contributing to the AFSPC operational baseline is the High Accuracy Satellite Drag Model. It incorporates near-real-time observations of LEO calibration satellites to estimate thermosphere density.

Both AFWA and SEC lack predictive models for several domains and continue to rely on conditional climatology and global indices as specification and forecast tools. This situation is the result of gaps in basic research understanding, undersampling of domains, and funding shortfalls and instabilities.

In summary, NSWP agencies and participants appear to recognize that major challenges remain in technology transfer, including model validation and how to link the best models together in a suitable framework that will be useful (and usable) by operational agencies. Another major challenge is the validation, and update as necessary, of linked models and their various modules.

3.6.4 Summary on Facilitating Transition to Operations

The Assessment Committee's investigations have shown that modeling capability in the NSWP will continue to improve as the existing relatively static "climate" models of the space environment become more dynamic and responsive to data assimilated in real time. The committee has found overwhelming evidence that space weather users and systems operators require local situational awareness through better data-infused specification ("nowcast") models. Users and operators also require accurate, data-driven models that provide 1–5 day forecasts tailored to their programmatic requirements. DOD-specific requirements are for 72-hour to 120-hour forecasts. The requirements of data assimilation in an operational environment are clearly a very high priority; civilian and military users require operational models that can assimilate real-time data and produce useful, understandable model outputs and forecasts.

Transitioning new knowledge from the research domain to the operations environment is a long, arduous process, replete with impediments. It requires assistance and advice from the researchers; it also requires a sizable, well-funded, and knowledgeable cadre of people in the operational units who can construct fast, efficient, and relatively "bulletproof" research codes. Some operational agencies such as NOAA/SEC and AFWA appear to be understaffed in this area and will likely require staff adjustments and augmentations (and perhaps some partnering) to achieve adequate capability. Efforts at the AFSPC on space weather and sensor requirements appear to be better staffed, but they need more direction and guidance. This area appears to require balancing of resources and the involvement of top-level management.

> ***Finding 3.8.*** There is an absence of suitable connection for "academia-to-operations" knowledge transfer and for the transition of research to operations in general.
>
> > ***Recommendation 3.8.1.*** The agencies involved in the NSWP should continue to support basic research modeling efforts and, if possible, provide increased resources for modeling that has space weather operational potential. New resources should be made available within NSWP agencies for transition of research models to an operational environment, including validation and revision of existing models. Present resources and human capital should be carefully evaluated, strategically invested, and wisely managed.

Improving the transition process will require quantitative assessments of the accuracy of data, models, and products, with overall progress to be measured in terms of improvements in these metrics. Although many models and many data streams exist, still lacking are quantitative estimates of the accuracy of this information that can be effectively communicated to users of space weather services. Effort is required toward the goal of continually refining the understanding of what information is needed operationally and how best to estimate and communicate its limitations to users. The NSWP cannot achieve the progress needed in providing space weather information without first quantifying current capabilities and then setting explicit targets for the future.

> ***Finding 3.9.*** There currently are few overall verification and validation methodologies that can be used to assess the reliability of space weather models and operational products.

Recommendation 3.9.1. The NSWP should establish standards for data and model archives and for access to them. The NSWP should establish standards for modeling frameworks in order to facilitate model coupling, flexible execution, and data assimilation.

Recommendation 3.9.2. The NSWP should work towards the establishment (and application) of metrics for space weather capabilities.

Micro-Satellites and Space Weather

Many important measurements—ground-based as well as space-based—that are needed for space weather applications do not require the precision of data returned by instruments used for scientific research. Thus, new space weather instruments and, in the case of space-based instrumentation, the spacecraft that launch them need not be as costly as the one-of-a-kind, high-precision instruments required for research. The NSWP would benefit from stronger emphases on technologies that miniaturize sensors to the point that some could even become part of the spacecraft skin. With such technologies, every spacecraft would, in essence, have the potential to become a space weather monitoring station. Extending observational coverage and space weather monitoring capabilities through miniature sensor development will ultimately enhance understanding and forecasting of the space environment.

FalconSAT-3 is an example of a student-built micro-satellite (weight typically on the order of 100 kg) that includes miniaturized space environment sensors as part of the payload. This micro-satellite has a mass of approximately 50 kg and will carry two space environment experiments. One experiment is the Flat Plasma Spectrometer for detecting nonthermal properties of plasma distribution functions and their association with growth of plasma density depletions. The second experiment is the Plasma Local Anomalous Noise Experiment for detecting plasma turbulence on different scale sizes. FalconSAT-3, which was designed, built, and tested by Air Force Academy cadets and faculty, is due to be delivered to Cape Canaveral Air Station in the fall of 2006.

Figure 3-5. The payload of a micro-satellite (FalconSAT-2).

In Figure 3-5, Dr. Geoff McHarg, Director of the Air Force Academy Space Physics and Atmospheric Research Center (SPARC), is shown with the payload of the earlier FalconSAT-2 micro-satellite. The payload is inside the rocket faring in this photograph, taken just prior to final checkout of the payload, payload interface, onboard computer, and solar cells. FalconSAT-2 was delivered to the launch site in early November 2005. Unfortunately the launch failed and the payload was lost. Despite the loss, micro-satellites of this type have great potential for space weather monitoring in LEO and medium Earth orbit (MEO).

Slightly larger satellites—the 200-400 kg mini-satellite class—also offer significant potential for space weather observations. Mini-satellites can return space weather measurements from geosynchronous Earth orbit (GEO) and from the L1 Lagrange point, where the ACE and SOHO science satellites currently reside.

3.7 Foster Education of Customers and the Public

The NSWP has shown success in many aspects of education: (a) professional education, (b) formal advanced education, (c) formal undergraduate education, and (d) informal public education.

In the professional realm, NOAA/SEC has played a key role in fostering the education of its customer base. In 2004, SEC published its first service assessment of a severe space weather storm event: the Halloween 2003 solar and geomagnetic storms. (See summary in Appendix F.) NOAA service assessments and NOAA/NWS responses to them are standard tools for internal and external communication of the formal assessment of particularly disruptive and damaging natural events.

On a broader level, SEC introduced Space Weather Storm Categories to provide perspective on space weather event severity in terms of geomagnetic storms, radio blackouts, and space radiation. NOAA has conducted targeted education sessions at Space Weather Week for individuals and for groups of industrial customers. In 2005, SEC added a 1-day pre-meeting education session that addressed many of the lessons learned from the strong storms of Solar Cycle 23. As SEC folds its activities into NWS/NCEP, it has begun providing space weather briefings at the annual American Meteorological Society meeting. These briefings are posted in the same venue as the daily terrestrial weather briefings. Effectively, SEC has begun "mainstreaming" space weather to professionals in allied disciplines.

Professional education activities are also on the rise in other agencies. These include the new NSF-sponsored professional publication, *Space Weather: The International Journal of Research and Applications*, space weather sessions at professional meetings sponsored by the American Geophysical Union, and a Space Weather Symposium at the annual meeting of the American Meteorological Society.

Mainstreaming of space weather within the DOD is also advancing. In late 2005, the AFSPC journal *High Frontier* carried a War Fighter Focus article entitled "Weather Situation Awareness and Joint Space Effects." A June 2005 *Physics Today* article authored by a NRL researcher dealt with relationships between space weather and Earth's climate. In a broader application, all U.S. Air Force pilots now routinely receive preflight briefings on the likelihood of high-frequency communications outages during their missions.

In the arena of formal advanced education, NSF/UARS granted bridge funding during 2005 for eight new tenure-track faculty positions, one each at eight universities. The grant competition received nearly 40 proposals from U.S. universities. Most of the positions have been filled, and new graduate opportunities are being developed with support from these faculty members. In a less-targeted effort, new graduate opportunities are arising in the NSF-funded Space Weather Science and Technology Center, CISM, and in the MURIs supported by DOD. CISM also supports a 2-week summer school aimed at introducing beginning graduate students to the breadth of space weather activities. A more advanced summer school was supported by the NCAR Advanced Studies Program in 2005. Counterbalancing this growth has been a downturn in NASA-supported research, which has typically provided the bulk of training in space weather instrument development.

The Decadal Research Strategy specifically recommended more support for undergraduate research and development of undergraduate research materials (NRC 2002, pp. 16–17, 136–140; see Appendix G for a list of the study's recommendations). Modest advances are evident in undergraduate space weather education. A new module on auroral physics, developed by a joint NCAR-Cooperative Meteorological Education and Training team, is available on CD or via the Internet. Two space weather–related textbooks are in development. One is targeted at the introductory undergraduate science level and is being tested at the University of California, Los Angeles. The second, whose development is funded by the DOD, is aimed at technical students who are not physics majors. Several universities have NASA or DOD funding for micro-satellite development. These programs are generally operating on small budgets with a handful of faculty. The slim operating margins rarely allow faculty to develop formal coursework in space weather education, although such courses would greatly benefit future spacecraft engineers and satellite operators.

Informal public education continues to strengthen. In the past 5 years, several popular books written for a broader audience have appeared. An IMAX movie, *Solar Max*, has played across the country. NASA has supported significant Internet-based education and public outreach activities aligned with space weather. The NCAR team supporting the Windows–to-the-Universe program reports that about 25 percent of Internet visitors to the site visit pages with space weather content. NASA's *Student Observer Network* provides comparison images, visualizations, and animations that align with national education standards. In the realm of popular content, *National Geographic Magazine* dedicated a substantial portion of the July 2004 edition to space weather storms. Television programs related to space weather have been developed by the Discovery Channel and NBC Universal, for television airing in 2006.

The advances discussed above make space weather materials and educational activities readily available to individuals who choose to seek out intellectual challenge and stimulation. The more difficult business of space weather education is ahead: developing materials for operators and decision makers (industry and governmental) who need to know about system vulnerabilities but are generally inclined to focus on narrower aspects of their own disciplines. In the years ahead, a focus of space weather education must be to make it interdisciplinary.

There is clear evidence that educational programs initiated because of the existence of the NSWP have produced a new awareness in the community (and in the public) of the "end-to-end" nature of the space environment as it affects national assets. This is a significant departure from the past, when space professionals tended to specialize in understanding certain portions of the solar-terrestrial chain but seldom took an overall systems view.

At the present time, some of the NSWP agencies show awareness of the need for workforce education and development in support of the national space weather effort. Other agencies are less clearly committed to workforce development. Nevertheless, all of the NSWP agencies have expressed the desire to maintain efforts to attract, educate, and continue to train a new cadre of space weather professionals.

Among these future professionals will be space scientists to do the basic space weather research and engineers to design and implement data acquisition hardware. It will also be important for a systems view of the Sun-Earth environment to be instilled in space weather forecasters and forecast users in the various operational agencies. The NSWP agencies will need to work with the academic community to encourage it to develop new approaches to attract science and engineering students who can become space weather professionals. Universities will need to provide new courses that educate students broadly by developing courses that demonstrate the highly interconnected character of the Sun-Earth system, especially as it applies to operational and forecast problems. NSWP agencies will also need to offer programs to aid in training students in an interdisciplinary and "cross-disciplinary" sense, as well as continuing education courses for their workforce. Advanced models and modeling frameworks will need to be developed and incorporated into academic courses. Approaches that bridge traditional university departmental boundaries will likely be required in many universities.

> ***Finding 3.10.*** There is a lack of a systematic approach to "grow" new space weather professionals.
>
> > ***Recommendation 3.10.1.*** The NSWP agencies should make a more unified and concerted effort to educate a new generation of professionals who have the systems view of space weather.

Space Weather Effects on Navigation

The Wide Area Augmentation System (WAAS) was designed by FAA and the DOT to become the future primary means of air navigation. WAAS was commissioned for vertical guidance approach (APV) services in July 2003. APV is a service level that guides an aircraft to 250 feet above a runway, even in conditions of poor visibility. The coverage area for the WAAS APV service is currently limited to the contiguous United States (CONUS). Analysis of WAAS performance since commissioning has shown limited availability of the APV service during extreme geomagnetic storm events.

In the WAAS system, the standard GPS service is augmented with corrections for time, the GPS satellite orbits, and the ionosphere. These augmentations enable the WAAS system to meet the very stringent aviation requirements for accuracy, availability and integrity. Quarterly performance reports have shown that the WAAS system generally meets or exceeds these requirements *(http://www.nstb.tc.faa.gov)*.

The performance reports also verify that one of the greatest challenges for WAAS is maintaining continuous APV availability during extreme geomagnetic storm events. Figure 3-6 illustrates this effect by plotting WAAS availability statistics and magnetic activity for an 8-month period surrounding the extreme storm events of October and November 2003. In the top half of the figure, the percent of the CONUS that had APV availability 95 percent of the time is plotted. In the bottom half, the daily minimum Disturbance Storm Time (Dst) is plotted as a proxy for geomagnetic activity. The largest drops in Dst indicate periods of extreme storm activity. Both plots cover the period from 1 July 2003 to 1 March 2004. The figures illustrate that during non-storm days, WAAS generally maintained 95 percent availability over 95 percent of the CONUS. During the extremely disturbed days of October 29-30 and November 20, 2003, however, the APV service was unavailable over the entire CONUS region for periods of approximately 15 and 10 hours, respectively.

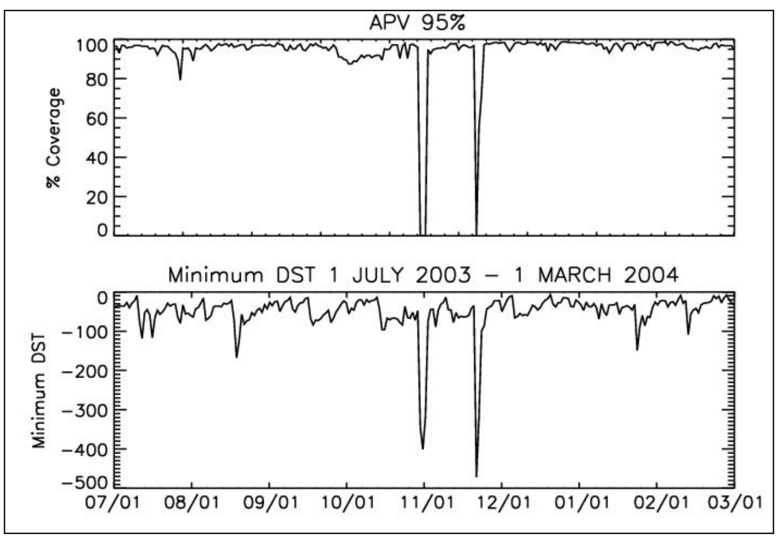

Figure 3-6. WAAS APV response to geomagnetic activity.

Incremental improvements for WAAS are planned with modernization efforts to extend the coverage region and improve availability. This will ultimately enable a greater level of precision approach services. Availability of the system, however, may continue to be challenged by the highly variable and unpredictable effects of extreme geomagnetic storms. Space weather studies that will employ new techniques and data sets to study these events are promising and may lead to a better WAAS system.

3.8 Crosscutting Issues

In the course of its fact-finding, the Assessment Committee identified two areas of concern that cut across several of the NSWP activities as defined in the 1995 Strategic Plan. Both private sector participation and international activities were discussed in previous NSWP documents under the Program Management activity, but their reach is, or should be, broader than just a management issue. The subsection on coordination with international space weather activities was substantially expanded in the 2000 Implementation Plan (OFCM 2000, pp. 7-14 to 7-18).

3.8.1 Private Sector Participation

The private sector has demonstrated interest in supplying tailored and unique space weather products and services as supplements to and enhancements of (added value to) the public products available from Government sources such as NOAA/SEC and AFWA. Companies are interested in supplying tailored products to both governmental and private-sector entities.

The good working relationships, as well as the tensions, between public and private sectors in the supply of space weather products at times mirror those that have existed in the atmospheric weather community for decades. These relationships and tensions can often lead to creative and enhanced responsiveness to user needs and requirements. Aspects of these relationships and related issues as applied to space weather vendors were addressed, with some suggestions for the future, in chapter 5 of the Decadal Research Strategy in Solar and Space Physics (NRC 2002).

When private space weather vendors supply other companies with space weather products, the details of the products often cannot be discussed because of the desire to protect intellectual property and safeguard proprietary information. Some industries are highly reluctant to share data that could be used adversely by a competitor (even if many in an industry might be suffering similar problems). Likewise, in the national security sector, classification of space weather anomaly data does not allow a wide and diverse examination of space weather effects. For these and related reasons, it is often difficult to obtain independent assessments of the cause(s) of some technical anomalies that might have a space weather origin or component.

In addition to supplying space weather products tailored to the needs of specific customer-users, the private sector appears to have some nascent interest in supplying observational data, from both ground- and space-based instruments, of use for both space weather monitoring and tailored products. These interests may even extend to supplying spacecraft specifically targeted to space weather applications. As discussed in Section 3.5, many types of space weather data for monitoring and prediction do not require the degree of precision that is demanded of similar data sets intended for scientific research. Thus, spacecraft and spacecraft instrument requirements (and therefore costs) could be substantially relaxed from those of science missions. With this change, the private sector may be able to formulate a business case for providing data critical to operational space weather monitoring, prediction, and analysis cost-effectively, once science missions are no longer operating.

> ***Finding 3.11*** The role of the private sector in space weather products, including potential for investment, is still being defined.

> ***Recommendation 3.11.1.*** The NSWP should work with the growing commercial sector for space weather services and products to enable this sector to flourish as a vital part of the national space weather program.
>
> ***Recommendation 3.11.2.*** The NSWP should work with the private sector to understand better the economic and social values of space weather knowledge and of products and services based on that knowledge.

In implementing these two recommendations, an industry-by-industry analysis would be highly beneficial.

3.8.2 International Collaboration

Individual agencies within the NSWP have pursued international collaboration for specific projects in both research and operations. For example, many of NASA's solar and solar-terrestrial research projects were developed and funded with international partners: SOHO, Cluster, and Ulysses with ESA; Geotail with Japan. The MetOp polar-orbiting operational environmental satellite, which will be launched and operated by the European Meteorological Satellites organization (EUMETSAT), will carry the Space Environment Monitor (SEM), a space weather senor supplied by NASA on behalf of NOAA. NOAA's National Geophysics Data Center operates the Space Physics Interactive Data Resource, a distributed international network of synchronous databases and middleware servers, containing space physics data accessed via the Internet. Finally, the USGS maintains agreements with international partners around the world for collecting and distributing geomagnetic data through the Intermagnet program of international ground-based observatories located throughout the world.

These efforts to encourage the collection and sharing of data from non-U.S. sources are carried out primarily though the efforts of each individual agency and are not well coordinated within the NSWP partnership. In effect, the NSWP has no international program. Nevertheless, the NSWP faces a potential loss of capability to protect the country's technological resources when several of the research satellites upon which it depends for data finally fail (as discussed in section 3.4). The NSWP needs to make much more extensive use of international cooperative efforts to gather and distribute space weather data by developing a coordinated plan for encouraging other countries to participate in these collection and distribution efforts. The broader the sources of accurate space weather data, the better the forecasts can be. A wider variety of space weather data sources than currently exist would also assist in assuring continuity of data if one or more U.S. sources fail.

> ***Finding 3.12.*** The NSWP has made relatively little effort to consider international partnering opportunities for collecting space weather data and distributing space weather information products. The worldwide space weather community would benefit by much more aggressive collection of space weather data by other countries.
>
> ***Recommendation 3.12.1.*** The NSWP should consider the benefits (and possible drawbacks) of establishing a formal international coordination mechanism for the

promotion, collection, and distribution of space weather data, including all forms of space weather data from satellites and ground-based sensors.

Such a program could be structured and operated along the lines of the Committee on Earth Observation Satellites (CEOS), which was formed in 1984 to address similar concerns within the Earth observations community. CEOS operates with minimal institutional resources and no central office. Nevertheless, it has been highly effective as the organizational basis for an international system of Earth observation satellites, which service the international needs for such data. The NSWP might even explore the option of establishing a coordinated, international effort under the aegis of CEOS. This option would allow the NSWP to make use of the established CEOS organization and its many members to explore the value of improved provision of space weather data for the world. Additional opportunities for data and research coordination may be possible through the ICSU-chartered International Space Environment Service (ISES).